Economic Considerations of Nuclear Power Deployment in Saudi Arabia

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Introduction

Saudi Arabia's plans to acquire nuclear power are ambiguous. In 2012, the kingdom announced its intention to build 16 nuclear reactors by 2032, which was later delayed to 2040.[1] More recently, the "Saudi Vision 2030", championed by the now Crown Prince, Mohamad Bin Salman, did not explicitly mention nuclear power as an option for the kingdom, though it emphasized the need to invest in, and localize renewable sources of energy.[2] The Saudi Vision 2030 was promptly followed by the "National Transformation Program 2020", which included the need to identify and the prepare the construction location of Saudi's first nuclear power plant, localize parts of the nuclear fuel cycle and the SMART small reactor, a South Korean technology.[3]

Saudi officials offer multiple motivations to construct nuclear power plants in the kingdom. Perhaps the most commonly articulated one is a desire to get away from the near-complete reliance on hydrocarbon resources to produce electricity and desalinated water. Such reliance is seen to lead to the depletion of national oil and gas reserves but is also perceived to have an opportunity cost associated with forgone export revenues. Others suggest that interest in nuclear power is also a response to Iran's acquisition of nuclear technology. It has been argued, for example, that, "GCC states want to show Iran, their own people, and the broader world that Arabs also have the prowess and power attributed to nuclear technology".[4] Whatever the motivations behind nuclear power might be, the acquisition of nuclear technology will entail major economic and non-economic costs.

This paper examines the main economic drawbacks and considerations for building nuclear power plants in Saudi Arabia. It focuses on issues such as large vis-à-vis small reactor options, cost of electricity generation, localization potential, and the role of renewables, particularly solar power. The paper also discusses the measures required and investments needed to achieve high penetration of renewables in the kingdom.

The Electricity Sector in Saudi Arabia

The kingdom's power generation capacity is built on conventional thermal plants fueled by a mix of crude oil, heavy fuel oil, natural gas and other petro-residuals, as shown in Figure 1.[5] All of the natural gas produced within the Kingdom is consumed domestically while electricity generation is dominated by gas turbines which offer a cheap way of meeting demand.[6] [7] The

Saudi Electric Company (SEC), a vertically integrated electricity company, controls 71% of the generation capacity and is responsible for transmission and distribution across the country.[7] More recently, government reforms are pushing for unbundling of the generation, transmission and distribution sectors in order to encourage the entry of new producers thereby increasing efficiency and decreasing government spending.[8]

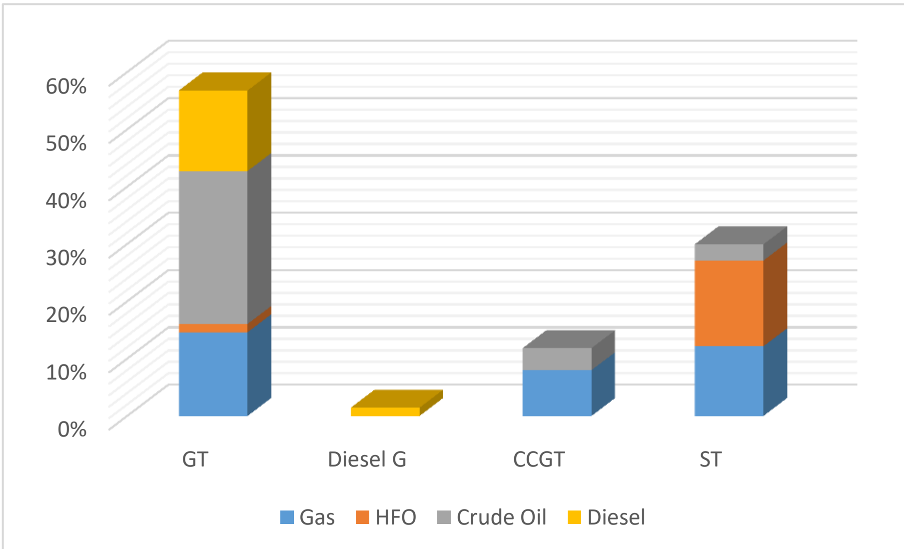
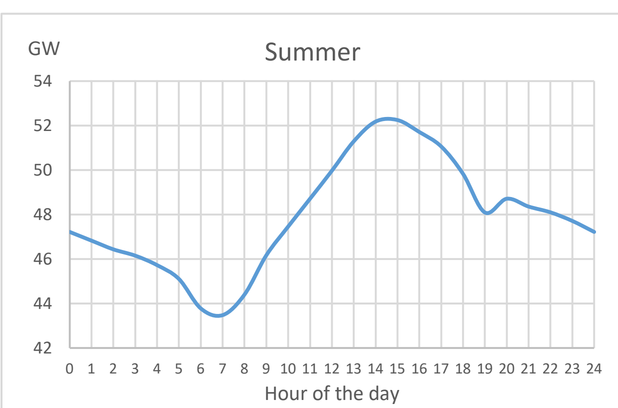


Figure 1: Electricity generation in Saudi Arabia by type of fuel and generation technology (ST= steam turbine, CCGT= Combined cycle gas Turbine, GT=Gas Turbine, Diesel Generators)

By 2032, power generation capacity in the kingdom is expected to reach 120 GW.[9] The increase in electricity demand will be mostly driven by population growth, a fast-growing economy and an increase in consumption fueled by cheap energy prices and high government subsidies.[10]
Based on 2014 data, the maximum peak load reached in Saudi Arabia was approximately 56.5 GW occurring during week 36 (September 1-7, 2014), while the minimum peak reached was 31.88 GW occurring during the first week of that same year (December 30-January 5, 2014). The high peak load occurred in summer and low peak load occurred in winter. The difference between highest and lowest load in summer was 8.77 GW, the difference in the winter was 7.55 GW.[11] The summer pattern is specific to a number of countries including the Gulf countries where air conditioning is widely used in summer and barely needed for heating in winter. See Figure 2.



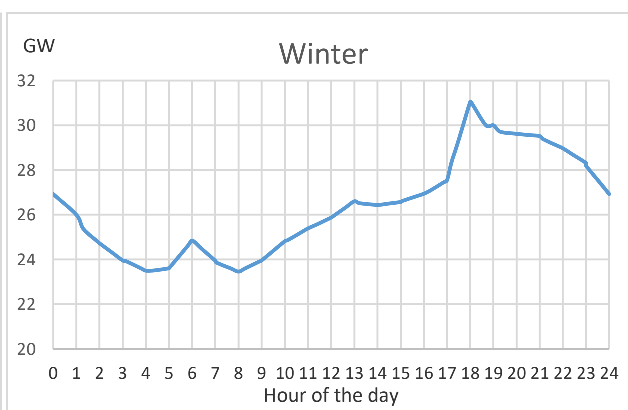


Figure 2: Hourly load in Saudi Arabia during summer (left) and winter (right) – Source: Chite and Ahmad, 2017

Nuclear Technology Options

There are multiple reactor technologies that are available for deployment in Saudi Arabia. Many of the reactors that have already been sold and are being operated or under construction have relatively large power capacities (Table 1).[12] More detailed technical descriptions of reactor technologies and their relevance to the Middle East market can be found in the literature.[13] In the Gulf Cooperation Council (GCC), the South Korean APR-1400 technology is the only one currently under construction in the United Arab Emirates.[14]

Table 1: Current reactor designs available for Saudi Arabia

Country	**Technology**	**Reactor Design**	**Capacity (MWe)**
South Korea	PWR	APR-1400	1400
France	PWR	EPR	1600-1700
USA/Japan	PWR	AP1000	1110
Russia	PWR	VVER	1000
USA/Japan	BWR	ABWR	1350
India/Canada	PHWR	PHWR/ACR-700	700

Saudi Arabia's ambitious plans for nuclear power has attracted a number of nuclear vendors. In 2013 both GE Hitachi Nuclear Energy and Toshiba/Westinghouse signed contracts with Exelon Nuclear Partners (ENP), a division of Exelon Generation, to pursue reactor construction deals with KA-CARE.[15] The reactor designs proposed include the ABWR, the ESBWR and the AP1000. The French companies Areva and EDF have also been aggressively moving into Saudi Arabia. In 2015, KA-CARE signed nuclear cooperation agreement with France to study the feasibility of constructing two EPR reactors while providing training on safety and waste disposal. Saudi Arabia and China signed a MoU in 2016 to build of High-temperature gas-cooled reactors (HTGRs) and in 2017 to study the feasibility of building HTGRs.[16]

More recently, Saudi Arabia sent a "request for information" to nuclear reactor vendors around the world, a step perceived as a first step towards opening a formal tender.[8] As a response, Westinghouse, which promotes the AP1000 design, has been reported to be in discussion with U.S.-based companies to forma bidding consortium.[9] With reports of Russian and South Korean companies also planning to bid, nuclear vendors worldwide look at Saudi Arabia as one of the most promising markets, especially with if KA-CARE's plan to build 16 reactors is materialized.

Small Modular Reactors

Saudi Arabia's interest in small modular reactors seems to be serious. In March 2015, the kingdom signed an MoU with South Korea to conduct a three-year study to review the feasibility of constructing SMART reactors in Saudi Arabia. The agreement also calls for the two countries to cooperate on the commercialization and promotion of the SMART reactor to third countries.[17]

A number of SMR developers have argued that there are multiple motivations to pursue smaller designs, directed both at large industrialized countries and developing countries. One motivation is the high upfront capital cost of standard reactors, which is beyond the financing capacities of many utilities and countries. Another is to expand nuclear power to countries with relatively small electrical-grid capacities; a gigawatt-scale reactor could destabilize a small grid. What is interesting about the SMART partnership between Saudi Arabia and South Korea is that the kingdom falls outside the "niche" SMR market, as advocated by SMR vendors.

However, other factors that have been offered as motivations for SMRs are claims to potentially greater safety due to the reliance on passive features, and enhancement in public acceptability. In the case of the Saudi SMART venture, the technology is also capable of producing desalinated water besides generation electricity.[18]

The downside of SMRs deployment in Saudi Arabia, however, is the loss of economies of scale – smaller nuclear reactors are typically more expensive on a per unit cost basis. Detailed and carefully conducted elicitations showed that even experts drawn from, or closely associated with, the nuclear industry expect SMRs to cost more per kW of capacity than currently operating reactors.[19] Based on the average of expert estimates of the extra per kW cost for SMRs, the percentage increase expected ranged from 12% for 225 MWe reactors to a whopping 120% for 45 MWe reactors.

There are currently dozens of SMR designs under development. Some of these are still in the conceptual design phase, many are still in the R&D phase and only four have been licensed or currently are under construction.[20] The details of these SMRs are summarized in Table 2. Thus far, there is no sign that any of the five remaining GCC countries are considering any of these reactors.

Country of Origin	**South Korea**	**Russia**	**China**	**Argentina**
Reactor Technology	PWR	PWR	HTGR	PWR
Status	Licensed	Under Construction	Under Construction	Under Construction
Electrical Power (MWe)	90-100	35	2X105	27

Table 2: Small modular reactors currently under construction or licensed

The HTGR Option

Saudi Arabia's interest in SMRs extends to the Chinese high temperature gas reactor (HTGR). In March 2017, KA-CARE and China Nuclear Engineering Group (CNEC) signed an agreement to conduct a feasibility study that will consider "the development of system solutions for the investment and construction of HTGRs".[21] The agreement will also examine cooperation in "intellectual property and the development of a domestic industrial supply chain for HTGRs built in Saudi Arabia".

Since HTGRs operate at a higher temperature compared to water-cooled reactors, they can be used to generate process heat and hydrogen production as well as electricity.[10] On paper, Saudi Arabia could deploy HTGRs in their industrial regions such as petrochemical compounds and heavy oil recovery systems. Proponents of HTGRs claim that they possess high safety standards.[22] However, based on a review of the operational history of HTGRs, they face some serious technical challenges and are prone to a variety of small failures such as air and oil ingress, which could trigger accidents with severe consequences.[11] [12] Given the importance of the oil and petrochemical sector for the Saudi economy, the consequences of any accident are likely to be immense. Therefore, the kingdom will be taking on a substantial risk for a return that can be achieved using other sources of energy and technologies.

Cost of Electricity Generation

The conventional way to compare the cost of electricity generated by different sources is to calculate the levelized cost of electricity (LCOE), which can be understood as the ratio of the total cost to the benefits (in this case the electricity produced) with all figures being discounted to the same baseline year. This follows from the standard discounted cash flow methodology, which accounts for the time-value of money. This methodology is used to calculate the life cycle cost of producing electricity.

The calculated LCOE for different energy sources are all busbar costs delivered to the grid; i.e., they take into account auxiliary or in-plant consumption of electricity but do not include transmission and distribution costs. Any large-scale expansion of nuclear power in Saudi Arabia would require an expansion of transmission infrastructure. Such costs are not included here, even though it could be significant.

The cost of electricity generated as well as water produced by desalination from any technology depends on a number of parameters. An important factor is the discount rate. For the case of Saudi Arabia, the chosen discount rate is 5 percent. Note that this is a real discount rate, and inflation is implicitly taken into account. This choice may seem somewhat low, but many studies do indeed adopt discount rates of around 5 to 5.5 percent in their evaluations of electricity economics in the GCC.[13]

Estimates of the cost of electricity generation of various sources in Saudi Arabia are shown in Table 3. These estimates were based on a recent study by Chite and Ahmad.[14] Estimating the cost of generation using prices of subsidized fuel, as usually entailed from Saudi electricity operators, results in very low generation costs where nuclear (and renewables) cannot compete.

[15]Fuel/ Technology	Nuclear	Gas-light oil / GT	Gas- light oil/ CCGT	Heavy Oil/ ST	Diesel/ Diesel
Fixed Cost ($/MWh)	68.5	10.37	17.35	14.77	66.98
Var. Cost(US$/MWh)	12.25	37.69	8.70	8.23	21.50
LCOE (cent/KWh)	8.08	4.81	2.60	2.30	8.85

Table 3: Cost of electricity generation in Saudi Arabia of different technologies using subsidized prices

A special case to be considered is the cost of nuclear electricity generated by SMRs. As discussed earlier, SMRs are expected to have higher capital costs per kW by somewhere between 12 and 120 percent.[16] In this analysis, SMRs' capital costs is assumed 25 percent higher than for current nuclear reactors, i.e., approximately $7,430/kW.[17] SMRs would also have higher fueling cost because of higher uranium requirements.[18] It is also not clear what sets of conditions they would be licensed under,[19] and depending on the safety and security requirements imposed by regulatory authorities, SMRs could have higher fixed and variable operations & maintenance costs. In contrast to these higher costs, the construction time for SMRs is expected to be shorter.[20] For simplicity, it is assumed that all of the cost variables for current (large) LWRs are the same as SMRs with the exception of the capital cost. Then, with these assumptions, the levelized cost of nuclear power from reactors rises from about $81/MWh if large reactors are constructed to over $94/MWh for SMRs.

Baseload Generation: Nuclear versus Natural Gas

Unlike renewables that have zero fueling costs, the cost of natural gas is an important, perhaps overwhelming, component of the cost of generating electricity in a natural gas plant. Therefore, the cost comparison between nuclear and natural gas could vary from country to country. Natural gas prices in countries that use domestic reserves, such as Saudi Arabia, would be significantly lower than countries that import natural gas at international prices, and this would affect the relative economics of power from nuclear reactors and natural gas plants.

The economic competitiveness of gas-fired power plants decreases as the prices of natural gas increase. Ahmad and Ramana estimated the cross-over value between nuclear and natural gas generated electricity for Saudi Arabia is at a natural gas price of $13.6/mmBTU.[21]
In other words, nuclear is less economical if natural gas prices are lower than the cross-over value. The economic prospects for nuclear power in the kingdom are not favorable in comparison with natural gas, even if the currently low domestic natural gas prices in Saudi Arabia were to rise substantially.

What if Saudi Arabia were to increase its domestic output and start exporting gas instead of using it in natural gas plants? This is related to what is often termed the opportunity cost. The first thing to note is that such exports will most likely be in a liquefied (LNG) form. Consequently, the costs associated with building infrastructure, liquefaction and shipping should be taken into account. A study on the future of natural gas conducted by the Massachusetts Institute of Technology estimates the cost of liquefaction at $2.15/mmBTU, shipping of LNG at $1.25/mmBTU, and regasification at $0.7/mmBTU.[22] The total of these costs amount to $4.1/mmBTU.[23] Because of this additional expenditure, it would make economical sense for

Saudi Arabia to build a nuclear reactor in comparison to a natural gas plant only if the price that could be obtained on the international market exceeds $13.6/mmBTU over the period of the lifetime of the reactor.

Potential of Solar Power in Saudi Arabia

Aside from meeting the increasing energy demand, integrating solar power in the Kingdom's current energy mix would be both economically and environmentally advantageous. Saudi Arabia has one of the highest potential of solar energy in the region where annual solar radiation is around 2,200 kWh/m^2.[24] Moreover, integrating renewables within the energy industry would drive economic diversification, create jobs and facilitate the implementation of climate change policies. Compared to nuclear, pairing solar power plants with domestic gas turbines can also help with load balancing more effectively.

The Kingdom recently equipped 30 metrological stations able to conduct very accurate measurements including one-minute measurements of Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), and Direct Normal Irradiance (DNI).[25] GHI ranged from an average daily total of 5,700 Wh/m^2 to the highest 6,700 Wh/m^2 with the higher values found in inland areas and lower values found on the coast. DNI values ranged from an average daily total of over 6,474 Wh/m^2 found on western inland areas to an average daily total closer to 5,510 Wh/m^2 found on eastern areas.[26] The solar resources outlined above are optimal for the performance of two main solar technologies that dominate current and future energy projects in Saudi Arabia: Photovoltaics (PV) and Concentrated Solar Power (CSP).

The hourly load pattern shown in Figure 2 above should offer an advantage for renewables mainly solar, as the high load occurs in the summer, in step with the maximum output of solar PV or CSP systems. However, PV systems generally suffer from reduced power output during the summer due to high ambient temperature affecting the performance of solar cells. On the other hand, CSP systems are less affected by high ambient temperature but are more sensitive to weather conditions like haze or sandstorms which lower the performance of solar CSP plants.[27]

In terms of costs, PV costs are divided into module costs (direct cost of photovoltaic modules); "hard" (inverter, racking, electrical equipment, etc.); and "soft costs" (labor, permitting fees, etc.). Module prices have followed a learning rate of 20 percent over the long term for the last 10 years.[28] Non-module prices, which are also known as BOS (Balance of System) are also decreasing, nearly at the same rate. Future improvements in the PV technology cost should come from a combination of improving power electronics, reducing supply chain complexity and cost, and decreasing installation costs and margins as markets mature.[29]

The dramatic decline in solar PV costs is particularly relevant because of the long construction period of nuclear projects, a decade at the very least.[30] Even assuming that a nuclear power project is given the go-ahead in 2018, it will likely be 2028 by the time it starts generating electricity. On the other hand, there is little reason to expect the costs of nuclear power to decline substantially. Historically, costs of nuclear power have only increased.[31]

Recent solar PV projects benefit from lower prices. For example, the Dewa project in Dubai rated 260 MW is priced at $328 million, giving a capital cost of 1,225 $/kW. The plant is expected to produce electricity at world record of 5.85 cent/kWh. Prices are heavily influenced by the project location. In Saudi Arabia, these costs should be less than those in the US and Europe. Costs should decrease even further as more PV projects are installed and some parts of the PV system are manufactured locally.

Investments Needs

The total investment for the 2012 KA-CARE plan is expected to reach about $360 billion by 2030, with CSP technologies representing the highest costs (see Figure 3).[32] A cheaper scenario involves adding gas turbines and replacing nuclear reactors with CCGT power plants which are cheaper and have a shorter construction time. In that case, the total investments needed are approximately $150 billion, nearly half the investments needed by 2012 KA-CARE plan (see Figure 4).

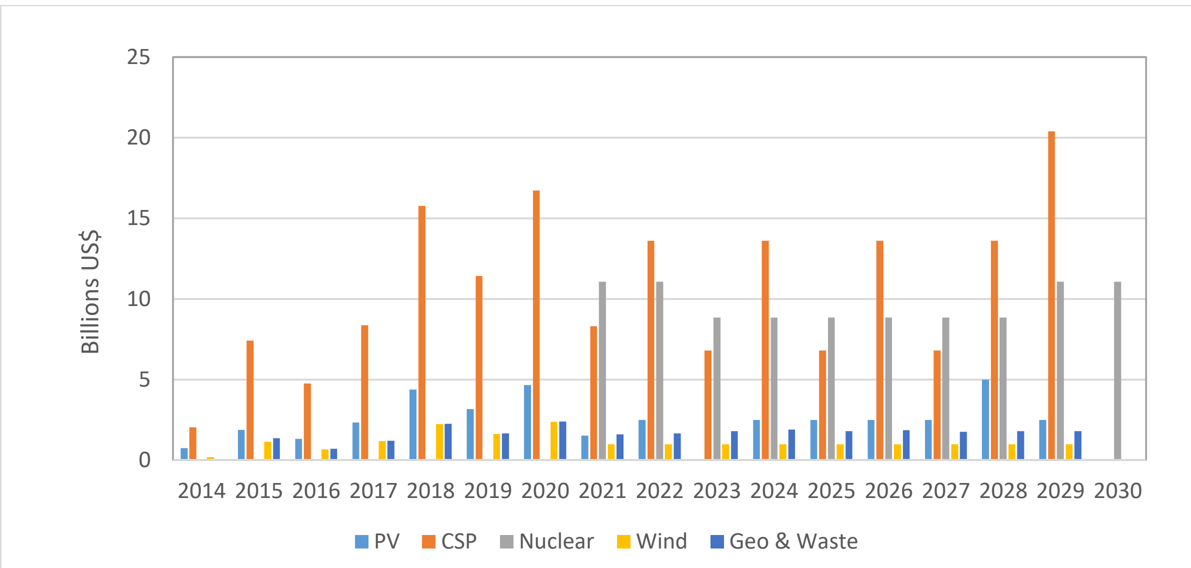


*Figure **3:** Investment in Billion US$ needed to implement the original KA-CARE plan (16 GW PV, 25 CSP and 17.6 GW Nuclear)*

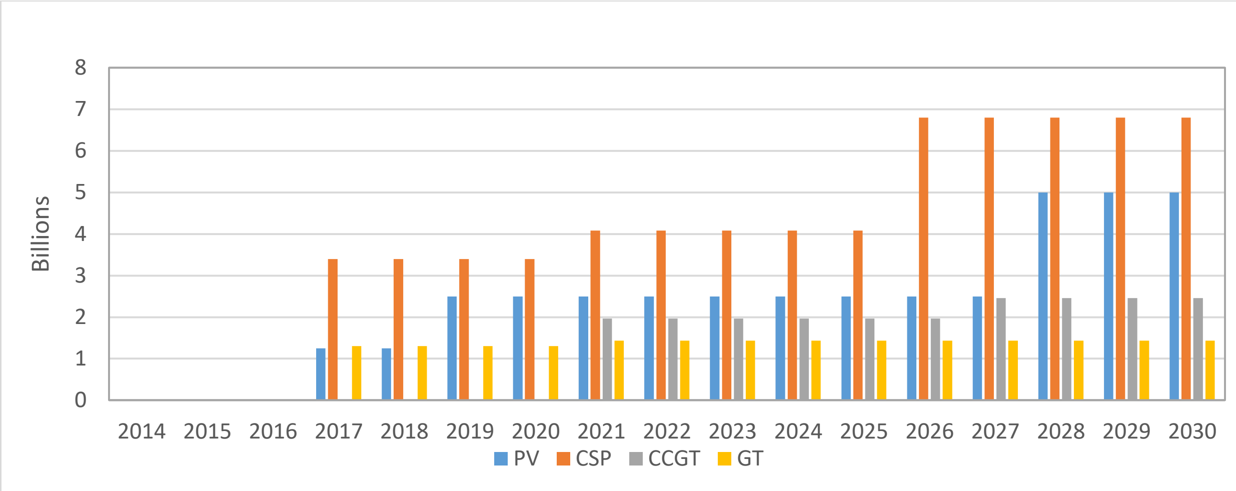


Figure 4: Investment in billion $ needed to implement the modified plan (16 GW PV, 10 CSP and 17.6 GW CGGT and 30 GW GT)

High solar penetration in the Saudi electricity sector will depend the support of the political leadership, the type of technology, its capacity and associated costs, the energy market structure, the investment climate and finally, the permitting rules and regulations.[42] The "Saudi Vision 2030" shows strong interest in renewables among political leaders, but the energy sector is still dominated by oil and remains highly subsidized which further leads to very low fuel and electricity prices encouraging high consumption.

All the existing entities needed for leading the energy transition are still new or yet to be established, however, it is likely that Saudi Aramco will play an important role in implementing this transition. Saudi Arabia will still need further research on the effect of sandstorms, soiling, aging and high temperatures on renewable energy systems. The country should also promote energy efficiency and storage schemes, smart grid systems and interconnection with neighboring countries. Moreover, the localization of renewables should be a top priority for policy makers since the kingdom can rely on international partnerships for technology transfers that could facilitate its energy transformation.

The Localization Question

Localization has been mentioned as an important theme in the Saudi 2030 vision, and was further emphasized in the National Transformation Plan 2020. In general, countries seek to promote local content requirements to promote public support, support new industries and add new jobs.

According to the National Transformation Plan 2020, the Saudi government aims to promote local content in the nuclear and renewable energy sector simultaneously.[43] For the nuclear energy sector, the kingdom plans to introduce nuclear power to the energy mix of the kingdom with a target of 25% to 30% local content that includes nuclear fuel cycle activities such as in uranium production.[33] To support the legislative efforts, building infrastructure, training human capabilities, localizing renewables technology, SMRs and the nuclear fuel cycle, 5 Billion Saudi Rial will be spent by 2020.[44]

Saudi Arabia's intention to localize nuclear industries and the fuel cycle clearly contradicts attempts by SMR vendors to cut costs through, factory-build, serial production models, unless the kingdom intends to build tens of SMART reactors across its territory. Though this does not seem to be a realistic option given the current lack of economic, industrial and human capacities. Furthermore, the possibility of linking all GCC countries with a one electric grid, makes the economic case for SMRs in the kingdom even weaker since such gird interconnections would be ideal to improve the economics of renewables.

On the other hand, the localization potential for renewables, particularly solar, in the kingdom is high. It is also easier to achieve compared to the complex, and political, nuclear localization. Additionally, it is not surprising that the decentralized decision-making process involved with planning and constructing renewable energy projects plays an important role in advancing its localization potential.

Investments in renewable energy in Saudi Arabia should be accompanied by localization of some part of the value chain in the kingdom. For PV, the localization of BOS (balance of the system) activities can be the first step; this could include manufacturing support structures, trackers, mounting hardware, electric protection devices, wiring, monitoring equipment and installation. As a second setup in localization the kingdom can build a manufacturing facility in the country. The investments needed for localizing a 1GW/yr PV manufacturing facility range between 1 and 2 billion US$ per plant. By 2030, a 7 GW PV plant should create around 21,000-50,000 direct jobs and 70,000-140,000 indirect jobs in the Kingdom.[45]

Conclusion

Nuclear power has been proposed as part of Saudi Arabia's future energy mix. With recent interest in investing in small modular reactors, the kingdom's strategy is both perplexing and risky. This work shows that nuclear power, large and small, does not meet the criterion of economic competitiveness. First, nuclear electricity is already more expensive than that produced by solar technologies. The coupling between renewables and natural gas offers Saudi Arabia the most economically optimal option. Given that the kingdom does not export its natural gas, the cross-over value between nuclear and natural gas was estimated at $13.6/mmBTU. For nuclear electricity to become a cheaper option, Saudi Arabia will have to sell its natural gas at higher prices than that of the cross-over price. On the other hand, renewables, particularly solar power, offers Saudi Arabia real opportunities for meeting its electricity demand incrementally with substantial localization potential.

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[12] There are numerous other designs that are potentially available for sale but these are not listed since they have so far not been constructed or under construction.

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[9] Ibid.

[17] WNN, "Saudi Arabia team up with South Korea on SMART", *World Nuclear News*, March 04, 2015, http://www.world-nuclear-news.org/NN-Saudi-Arabia-teams-up-with-Korea-on-SMART-0403154.html

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[19] Ahmed Abdulla, Inês Lima Azevedo, and M. Granger Morgan, "Expert Assessments of the Cost of Light Water Small Modular Reactors," *Proceedings of the National Academy of Sciences* 110, no. 24 (2013): 9686–91.

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[21] WNN, "China, Saudi Arabia begin HTGR feasibility study", *World Nuclear News*, May 17, 2015, http://www.world-nuclear-news.org/NN-China-Saudi-Arabia-begin-HTGR-feasibility-study-1705174.html

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[28] http://trade.ec.europa.eu/doclib/press/index.cfm?id=1461.
[29] *Ibid.*
[30] According to the IAEA's figures for construction periods, the global weighted average reactor construction time is 96.6 months, or about eight years. See IAEA, *Nuclear Power Reactors in the World: 2013 Edition* (Vienna: International Atomic Energy Agency, 2013). In these figures, the construction period is defined as the time between the "first pouring of concrete to the connection of the unit to the grid". However, some costs that are incurred before the first pour of concrete—for example, money spent on ordering components that take a long time to manufacture. If one were to include those as well, there would be cash flows from a project initiation for about ten years.
[31] Hultman and Koomey, "The Risk of Surprise in Energy Technology Costs"; Arnulf Grubler, "The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing," *Energy Policy* 38, no. 9 (2010): 5174–88.
[32] Calculations used the following capital costs: 2,500 $/ KW for PV, 6,800 $/KW for CSP with six hours storage and $5,530 for nuclear reactor Olson, Schlag, Patel, and Kwok, *Capital Cost Review of Power Generation Technologies;* Ali Ahmad, and M.V. Ramana, Too Costly to Matter: Economics of Nuclear Power for Saudi Arabia. *Energy* 69 (2014): 682-694
[42] *Moving towards 100% Renewable Electricity in Europe & North Africa by 2050: Evaluating progress in 2010.* PricewaterhouseCoopers, 2011.
[43] National Transformation Program. (2016). Retrieved October 2, 2017, from http://vision2030.gov.sa/en/ntp
[33] It is not clear for now whether "uranium production" includes enrichment.
[44] Ibid.
[45] A typical PV plant will need two persons/ MW in the construction stage, 7.5 person/ MW in the operation stage, and 0.5 person/ MW for maintenance. In 2012, the PV industry created 3-7 direct jobs and 10-20 indirect jobs per MW produced. *Energy from the Desert: Very Large scale PV Plants for Shifiting to Renewable Energy Value.* s.l. : IEA - PVPS T8-01, 2015